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METHODS FOR DC TO AC CONVERSION

SEMI-ANNUAL STATUS REPORT

By

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1.0 Introduction

In the interim since the last report, effort has been directed toward (1) establishing experimental procedures for a study of thin film devices with application to switching; (2) setting up experimental procedures to establish the factors affecting the magnetoresistance ratios of bismuth corbino disks formed under varying conditions; (3) setting up the new liquid helium experimental apparatus centered around the recently acquired glass dewar; (4) considering initial design for the flux shielding experiments; and (5) continuing an extensive literature search in the field of thin film devices, some of which was introduced in the previous report. Because of the recent wave of interest in this field, publications at present are considerable.

Two meetings on thin film devices were attended in this interim period. The first was the First Annual Meeting on Vacuum Science and Technology which was held recently in Albuquerque. Most company representatives were disinclined to release specific fabrication methods, but these can probably be gleaned from the literature in the near future. Some new devices were introduced which were for the most part thin-film transistors rather than field-effect type devices: however, the thin film technology associated with them is of interest.

The second meeting was a lecture and demonstration given at Kirtland AFB Special Weapons Center on June 18, 1965 by

two Melpar scientists. These workers have considerable experimental experience and were able to convey some interesting information on materials and techniques which should be useful.

2.0 Thin Films

2.1 Active Devices of Interest

2.2 MOS Insulated Gate Transistor

The so-called MOS (metal-oxide-semiconductor) insulated-gate transistor has characteristics attractive to many applications, but unfortunately, one of these is an extremely high input impedance which may rule this device out for inverter switching applications even for multi-device (parallel) systems. It is hoped that a suitable compromise can be reached between tolerable pinch-off voltages and response times versus film thicknesses.

The MOS transistor is a majority-carrier device in which the current in a conducting channel is modulated by a gate voltage in a typical field-effect manner. Successful MOS devices have been constructed in the surface of a single crystal of silicon,¹ by using thin-films of cadmium selenide,² and by using thin-films of cadmium sulfide.³

¹F.P. Herman and S.R. Hofstein, "The Insulated-Gate Field-Effect Transistor" presented at the Electron Devices Meeting, Washington, D.C., October, 1962. (Attended by the authors) Published Proc. IEEE, Vol. 51, (1963), 1190.

²F.V. Shallcross, "Cadmium Selenide Thin-Film Transistors," Proc. IEEE, Vol. 51, (1963), 851; and F.V. Shallcross, "Evaluation of Cadmium Selenide Films for Use in Thin-Film Transistors," RCA Review, Vol. 24, (1963), 676.

³P.K. Weimer, "The TFT - A New Thin-Film Transistor," Proc. IEEE, Vol. 50, (1962), 1462; and H. Borhan and P.K. Weimer, "An Analysis of the Characteristics of Insulated-Gate Thin-Film Transistors," RCA Review, Vol. 24, (1963), 153.

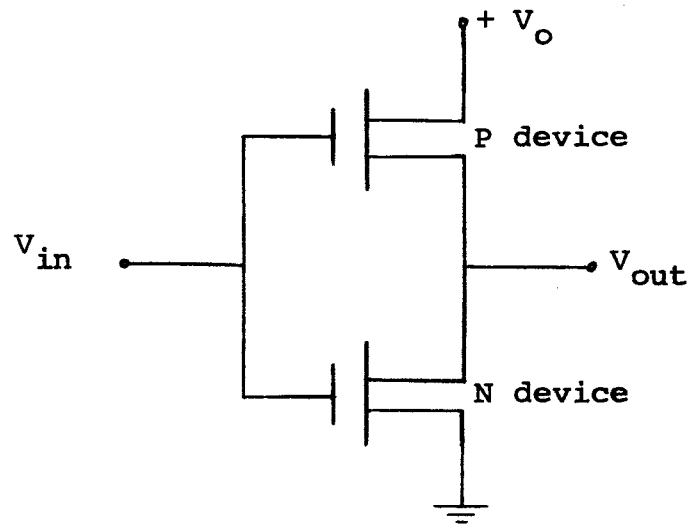
A typical plan-view of an MOS device was illustrated previously⁴ and is characteristic regardless of the material used. The CdS and CdSe devices are both N-type but the silicon devices can be N-type or P-type by respective choice of doped silicon. It is understood that P-type devices have also been constructed, using tellurium, at Melpar and RCA.

Upon studying the various articles on CdS and CdSe devices it became quite evident that CdSe material would be superior to CdS for the thin film study to be conducted soon. This would be particularly evident in the evaporation procedure. In evaporating cadmium sulfide the vacuum system evidently becomes contaminated throughout with sulfur no matter what extremes are used in shielding. Also, presently, no electrical advantage seems to be gained in using CdS rather than CdSe. Additionally, the vapor pressure of selenium is near that of cadmium, but much lower than sulfur at a given temperature.

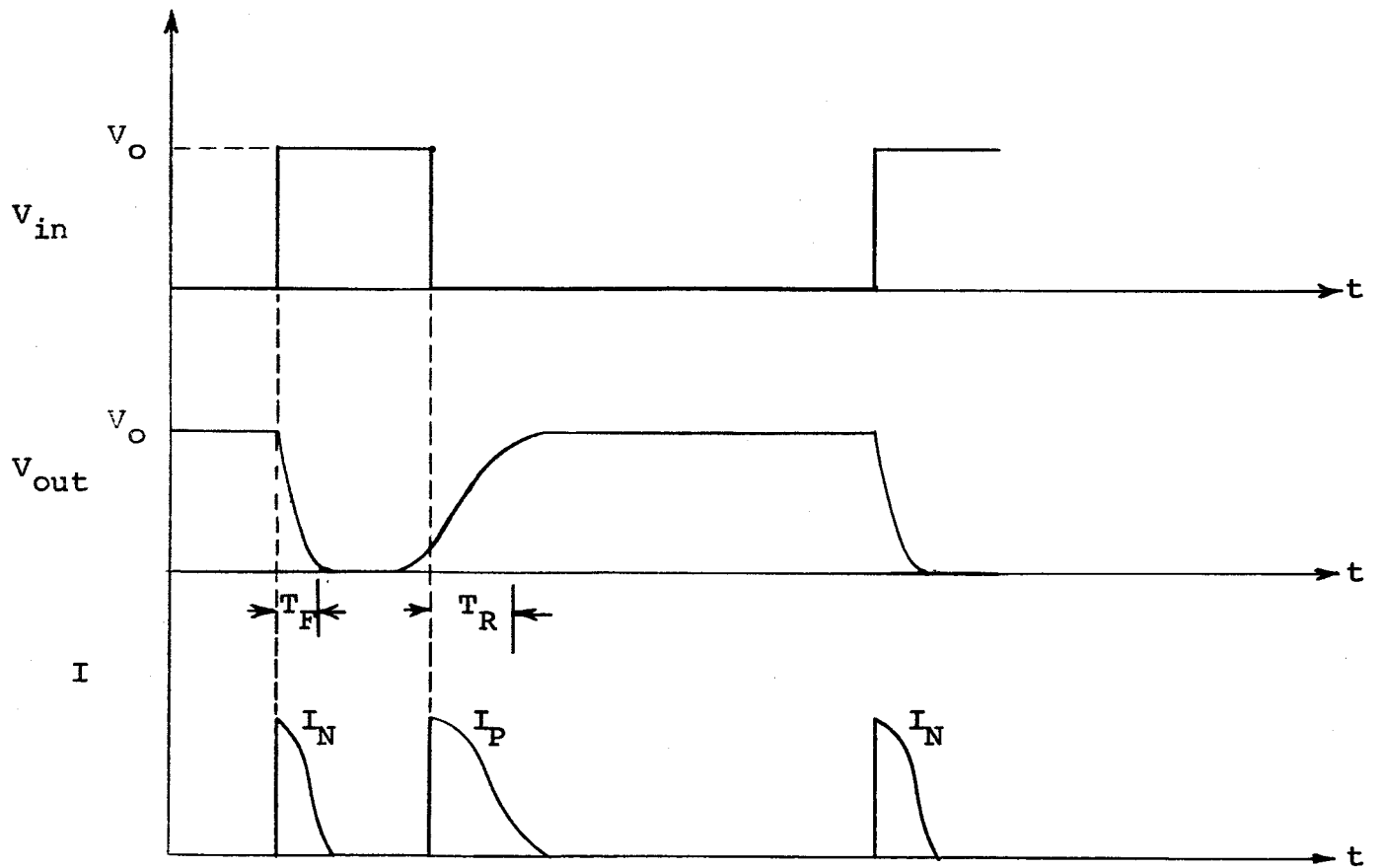
An N-P inverter has been tested for shut-off time,⁵ but evidence of on-off rates for single devices is somewhat spotty. For the two-device basic inverter circuit shown in Figure 1, a turn-on rise time (T_R) of 36 microseconds and a turn-on fall time (T_F) of 25 microseconds was recorded for a square wave input. It is believed that single device response to square-wave gate waveforms should be in the nanosecond range.

⁴P.K. Weimer, F.V. Shallcross, and H. Barkan, "Coplanar-Electrode Insulated-Gate Thin-Film Transistors," RCA Review, Vol. 24, (1963), 661; and R. Bechtel and W.W. Grannemann, "Methods for DC to AC Conversion," UNM Engr. Experiment Station PR-62, (1965), 19.

⁵J.R. Burns, "Switching Response of Complementary-Symmetry MOS Transistor Logic Circuits," RCA Review, Vol. 24, (1964), 627.



(a)

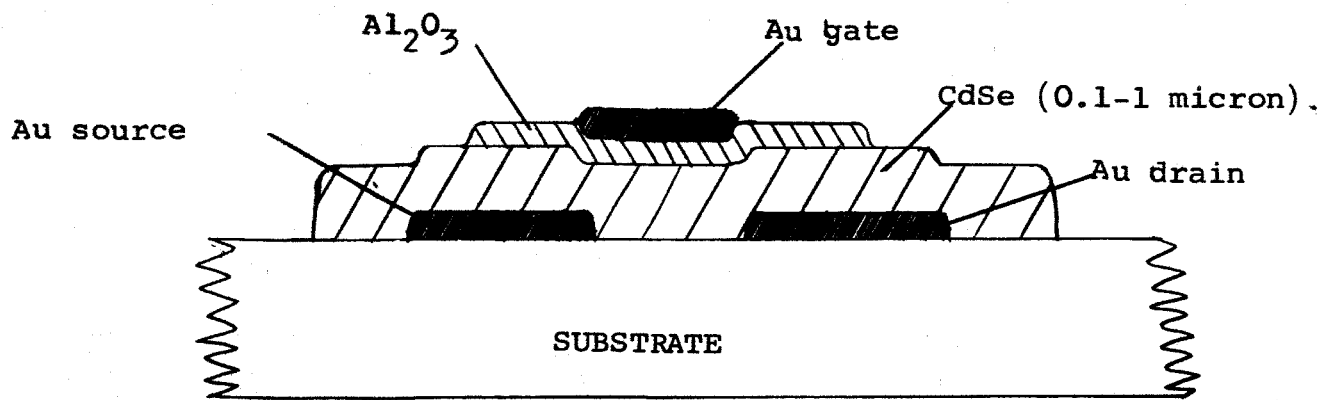


(b)

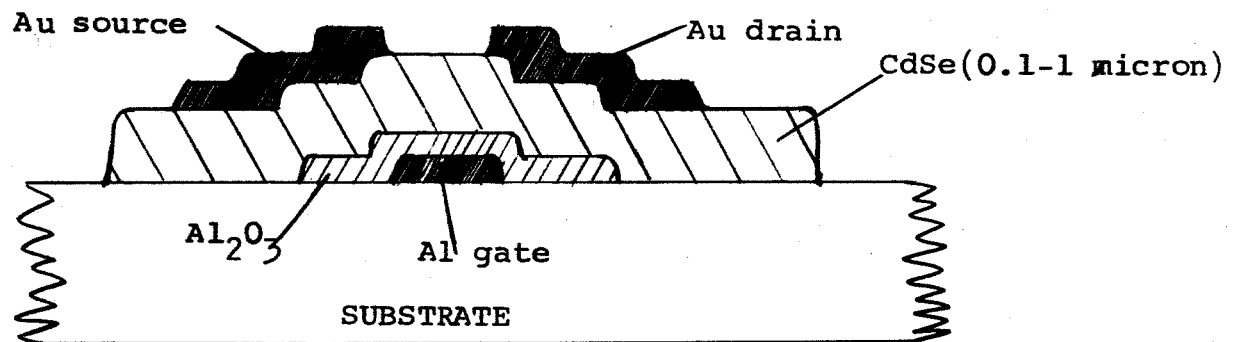
Figure 1. (a) Basic MOS Inverter Circuit
(b) Square-Wave Input Response

Of course, there are the several variations of the standard MOS transistor described previously, which are also field-effect devices (See Bechtel, Note 4). An addition is another variation called the coplanar-electrode insulated-gate thin-film transistor (See Weiner, Note 4). The electrode arrangement that characterizes the coplanar device (Figure 2, showing a comparison of this and two more-common units) is said to better facilitate fabrication and to result in on-to-off current ratios on the order of 10^7 . Higher spacing precision is obtained by depositing all electrodes on the semiconductor - which results in all electrodes being on the same side of the semiconductor. This is in contrast to the other variations which incorporate an interspersion of electrodes.

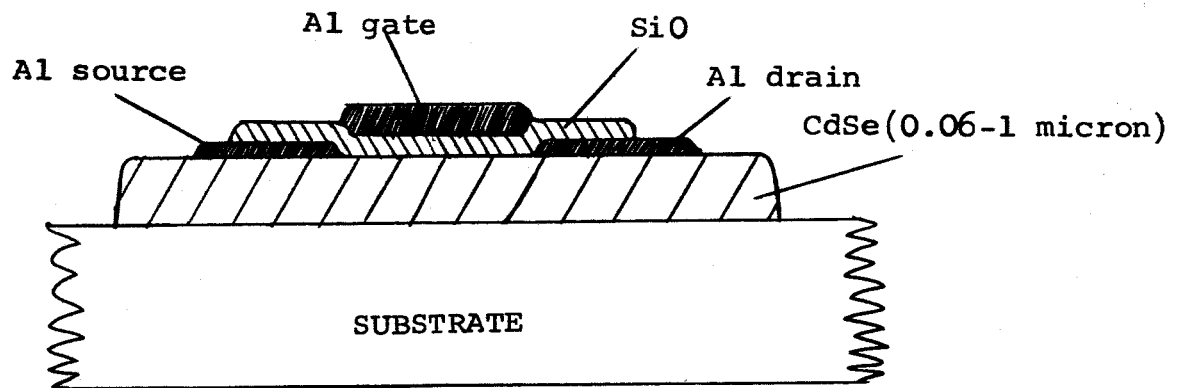
The gate voltage required for onset (or pinch-off) of drain current is typically around -3 volts. One must realize, however, that these devices as presently formed have an extremely high input impedance. If the impedance is to be decreased by increasing the film thickness, this action will necessarily increase the pinch-off voltage. A compromise will have to be reached in which paralleling several devices will reach final impedance lows. This compromise study will be a necessary inclusion in further study of MOS devices for switching.



(a)



(b)



(c)

Figure 2. (a) Staggered-Layer MOS Device
(b) Inverted-Staggered MOS Device
(c) Coplanar MOS Device

2.2 Thin-Film Deposition for MOS Devices

Although procedures in depositing thin films of CdS and CdSe vary a great deal, one fact is common to all: the film properties are nearly totally unpredictable from the bulk properties. Extreme variations seem to be quite common. Also, for the materials that have been mentioned in connection with MOS devices, there appears to be no advantage in "sputtering" instead of using straight evaporation processes (as far as the properties of the film are concerned). However, the compound materials can be readily deposited in film form by sputtering, and for certain materials this would be a definite advantage because evaporation frequently results in dissociation. For still other materials, silicon, for instance, the technique of chemical vapor deposition offers the advantage of relative ease over both evaporation and sputtering.

Interestingly enough, it has been shown that for the most part film properties are essentially insensitive to background pressure during film formation.⁶ Germanium films formed at 10^{-8} mm Hg had properties essentially similar to film formed at 10^{-5} mm Hg.

Criteria involving deposition rates, temperatures, and material selection along with substrate selection, cleaning methods, and co-heating are readily available in the literature and have been compiled for ready use. They will not be covered here since they are extensive and, for various reasons, some may never be used.

⁶J.F. Ambrose, et al., "Molecular Circuit Development," Melpar Quarterly Report No. 11, AO 400, Vol. 119, 11.

It is believed that the deposition requirements for most of the materials of interest are fully within the capabilities of equipment currently on hand at this laboratory. In addition, it should be pointed out that substantial experience has already been gained in thin-film deposition work through various other projects at this laboratory.

3.0 Impurity Effects in Bismuth Corbino Disks

For the flux-shielding experiments it will be advantageous to use corbino disks with high magnetoresistance ratios. There is experimental evidence that the ratios that have recently been obtained using corbino disks molded in ultra-pure carbon molds are poorer than those obtained originally using locally available low-grade carbon. The switch to the ultra-pure forms was made for two reasons: (1) the high-grade material was available in 4 inch diameter rods as opposed to 2-1/4 inch diameter rods for the low-grade material, and thus larger disks could be formed; (2) it was believed that there may have been too much impurity or too many contaminants in the low-grade material such as to reduce the magnetoresistance ratio. One may recall that earlier evidence had indicated that over-doping to a very minute degree from very minute levels reduced the magnetoresistance ratio without exception. Apparently the proper doping level is somewhat less than those attempted earlier.

For the initial experimentation molds have been machined out of each of the carbon materials; they are

the same dimensions. As nearly as possible, a bismuth corbino disk will be formed in each mold, at the same time, under the same conditions. The vacuum chamber is now under minor modification to allow this. This procedure will be repeated under varying degrees of pre-cleaning and outgassing until a definite differential trend is detected. Then controlled doping will follow using those materials which are impurities in the low-grade mold material.

The magnetoresistance measurements will be made in the new glass dewar using liquid nitrogen. There is no reason to believe that a decrease in magnetoresistance ratio would take place in going from liquid nitrogen temperatures to liquid helium temperatures; therefore, the check at 80°K should be sufficient and cost considerably less.

Effort will be made to construct the samples in such a way as to reduce mechanical stresses at reduced temperature due to differing thermal contraction between materials. This will involve, for example, segmenting the circumferential contact on the corbino disks. Careful choice in the location of solder joints is also of necessity.

4.0 Cryogenics

4.1 New Material Advances

At present niobium alloys stand in the forefront of superconductive material development, since these alloys possess the highest known critical temperature ($\sim 18^{\circ}\text{K}$).

Until recently this material has been limited in use due to available forms. In 1964 RCA successfully deposited niobium stannide (Nb_3Sn) of a very good quality on a steel ribbon, for use in a superconducting magnet.⁷ By using a vapor transport technique which permits continuous deposition with high mechanical strength, lengths up to one kilometer were readily produced. A solenoid magnet, wound using Nb_3Sn coated steel ribbon, generated fields of 107 kilogauss in a one inch bore. However, the points concerning this material of most interest to the inverter project are its high transition temperature, critical current density, and ability to be deposited in thin film of exceptional quality and useability.

The RCA vapor transport technique involves the hydrogen reduction chlorides of niobium and tin on a properly heated substrate at temperatures generally between 900°C and 1200°C.⁸

Some important properties related to a vapor deposited Nb_3Sn sample are:

Maximum Observed Critical Transition Temperature	Possible Deposition Temperature	London ⁹ Penetration Depth	¹⁰ Resistivity	Critical ¹¹ Current Density
18.3°K	675 to 1600°C	~2900 Å	~1.2x10 ⁻⁵ ohm-cm at T > T _c	~15x10 ⁵ amp/cm ² at zero field

⁷H.C. Schindler and E.R. Nyman, "Electromagnetic Performance of Niobium-Stannide Ribbon," RCA Review, Vol. 25, No. 3, (1964), 570.

⁸J.J. Hanak, K. Strater, and G.W. Allen, "Preparation and Properties of Vapor-Deposited Niobium-Stannide," RCA Review, Vol. 25, No. 4, (1964), 342.

⁹G.D. Cody, "The Superconducting Penetration Depth of Niobium-Stannide," RCA Review, Vol. 25, No. 3, (1964), 414.

¹⁰D.W. Woodard and G.D. Cody, "Anomalous Resistivity of Niobium Stannide," RCA Review, Vol. 25, No. 3, (1964), 393.

¹¹G.D. Cody and G.W. Cullen, "Critical Currents and Lorentz-Force Model in Niobium Stannide," RCA Review, Vol. 25, No. 3, (1964), 466.

It is foreseeable that niobium stannide ribbon could have total usage for the gated-magnetic field (GMF) inverter in the capacity of both the shield material and the magnet. It was mentioned that either an electromagnet or a permanent magnet could be used in the GMF inverter. The permanent magnet could further be of the ordinary type or superconducting type.¹² The latter would permit a closed superconducting system.

The possibility of making superconducting permanent magnets exists because of the lossless current flow property of a superconductor. The superconducting magnet operation begins with an initial inductive charging, usually by means of an external magnet whereupon the field remains trapped in the cylinder for as long as it is kept superconducting. A hard (high-field) superconductor such as niobium stannide has been found to have an energy product over 25×10^6 gauss-oersteds, and it is likely that this figure could readily be exceeded as future exploration reveals new materials.

The magnets are typically formed by deposition of superconducting material onto a cylindrical substrate. However, to reduce the characteristic flux jump (sudden persistent current loss) that one encounters with these cylindrical forms, a technique of using a composite cylinder made up of thin superconducting disks insulated one from the other has been described.¹³ (This is somewhat analogous to the laminating

¹²C.P. Bean, and M.V. Doyle, "Superconductors as Permanent Magnets," J. Applied Physics, Vol. 34, (1963), 1364.

¹³J.J. Hanak, "Magnetization of Niobium-Stannide Films in Transverse Fields," RCA Review, Vol. 25, No. 3, (1964), 551.

of a transformer to reduce eddy-current losses.) The disks are further etched, down to the substrate, into concentric rings. After assembly, the magnet resembles what one would obtain by slicing a multi-cylinder co-axial tube in which the cylinders are insulated one from the other, the slices then being stacked and insulated from each other. It was found that the stacking technique improved the problem of flux jumping over the straight cylinder magnet and that the ring-technique improved the situation further still. In the case of the magnet, highly conducting non-superconducting metal is used for the insulator-separating disks. The laminated magnet is less easily constructed than the standard cylindrical type, so technologically a compromise between simplicity and stability would have to be made.

4.2 Deposition of Niobium Films

As pointed out in the last report one phase of the GME inverter study will require high-quality niobium films of quite broad thickness extremes. Some interesting new deposition methods are described briefly below for niobium, the deposition of which has presented quite a problem in the past.

4.2.1 Exploding Wire Method¹⁴

With this method wire material is evaporated by capacitor discharge in an inert atmosphere rather than in a vacuum. The inherent fast transit time (10^{-5} sec) of the material from source to substrate results in less impurity

¹⁴M. Garbung, M. Gottlieb, and J.J. Conroy, "Hard Super-Conducting Films from Exploding Wires," J. Applied Physics, Vol. 34, No. 12, (1963), 3642.

gettering as the vaporized material travels from source to the substrate. Thus pure films are possible. With an energy discharge of about 100 joules from a condenser bank, hard superconducting films of several hundred angstroms thickness, having a critical magnetic field of about eleven kilogauss, are reported. However, a prevailing disadvantage in this method of deposition is the difficulty in achieving uniform thicknesses.

Very little set-up work would be needed to employ this method for depositing niobium film in this laboratory. Most of the equipment is now on hand.

4.2.2 Asymmetric AC Sputtering¹⁵

With this method a reverse sputtering current is used to bombard the film during the deposition process. This effectively removes gaseous impurities to obtain pure films. It is reported that films having critical temperatures within 0.2 percent of that of the bulk material are repeatedly obtained. The films are also quite uniform.

One disadvantage of this method is the requirement of special apparatus, since the substrate must be heated to 500°C and there must be removable shielding for the presputtering period. Also, a cylindrical cathode is used. Still, the CVC vacuum system could be modified to meet these requirements, but it would require somewhat more work than the exploding wire method.

¹⁵R. Frerichs and C.J. Kircher, "Properties of Superconducting Niobium Films by Asymmetric AC Sputtering," J. Applied Physics, Vol. 34, (1963), 3541.

4.2.3 Bias Sputtering¹⁶

This slight modification in the standard sputtering scheme is said to result in purer films because ion clean-up is in operation during the entire deposition process. Biasing the substrate allows removal of impurities that have come from the cathode itself. Success with glass substrates is reported when a small positive bias is applied initially by admitting about 1 percent of oxygen into the sputtering gas. Then the bias is switched to the desired negative value, and the sputtering is completed in pure argon.

4.2.4 Vapor Deposition

This more standard deposition method has seen some improvement with regard to niobium films.¹⁷ The strong gettering action for oxygen that niobium possesses has been used to reduce the partial pressure of this gas in the vacuum system. By use of a shutter arrangement between the source and substrate, pre-evaporation of the source material is allowed which in turn leads to oxygen removal by gettering. The substrates are then exposed to the source material which had been previously outgassed in a high vacuum.

It is believed that any one of the above methods is within the capability of equipment now on hand, in some cases with very little modification.

¹⁶L.I. Maissel and P.M. Schaible, "Thin Films Deposited by Bias Sputtering," J. Applied Physics, Vol. 36, (1965), 237.

¹⁷C.A. Neugebauer and R.A. Ekvall, "Vapor-Deposited Superconductive Films of Nb, Ta, and V," J. Applied Physics, Vol. 35, (1964), 547.

5.0 Work Schedule Outline

In this and the last report new problems and supporting experimental procedures have been proposed and discussed with some indication of future work scheduling. Present plans call for the following schedule:

1. Obtain immediate evidence that would indicate eventual success of the gated-magnetic-field inverter. For the shielding capability checks, this will involve flux measurements external and internal to various shield specimens (probably niobium) most likely by use of magnetoresistors.

Switching time studies will follow for the various shield specimens (varying thicknesses) to study the effect of thickness, purity and deposition method on switching time (and shielding capability, too, for that matter). The switching time study will necessarily involve the effects of shield geometry and a switching-coil arrangement, which must be kept at a low inductance. Ideally, the geometry should be as simple as possible.. A planar or cylindrical shield would be relatively simple as opposed to a spherical shape. A spherical shape would present difficulties both in thin-film coating and switching efficiency.

2. Conduct an experimental study in the field of thin-film devices of the types that have been described to establish eventual success of these devices in high current-low voltage inverter applications. This will involve establishing the pinch-off voltage - film thickness dependence, and thus the

related impedance level lower limits. The film thickness will be steadily increased, from the first sample constructed, in subsequent samples. The pinch-off voltage will be checked with each until some imposed, tolerable, upper limit is reached. After measuring the "on" impedance of this optimum device one can judge how practical or feasible it might be to parallel several such devices to form an efficient low voltage - high current inverter.

3. Initiate, where applicable, a search for theoretical models for each of the above areas described. This might be a system model for the GMF rather than a particular device model.